Recent Physics Results with the COMPASS Experiment

Stephan Paul
for the COMPASS Collaboration

Technische Universität München, Physik Department E18
James-Franck Strasse, D-85478 Garching

Abstract. The COMPASS experiment has obtained first physics results in the field of polarized distribution functions for quarks and gluons using muon scattering off polarized deuterons. The analysis using open charm production and pairs of high p_T hadrons is presented. We also have used a transversely polarized target to address transverse information for quarks inside the nucleon. In addition, a pilot run with incoming pions taken late 2004 will give first information on the pion polarizabilities and hadron resonances. The physics prospects from this run as well as from future data taking in this field are also outlined.

INTRODUCTION

The structure of hadrons can be investigated at different length scales revealing different properties and descriptions of hadrons. At small distance scales (large Q^2), deep inelastic scattering reveals the nucleon structure in terms of current quarks and gluons, using structure functions. The hot topic are spin degrees of freedom, the understanding of the nucleons spin in the interplay of its constituents. At medium distance scales the tool of spectroscopy is useful, a domain still dominated by the language of constituent quarks. The search for exotic quantum numbers and glueballs at masses between 1.5 and 2.5 GeV/c^2 should reveal more insights to the phenomenon of confinement. Very large distance scales probe quasi static hadron properties like polarizabilities of mesons. Effective field theories derived from QCD are expected to give a consistent description of the low energy quantities. The COMPASS experiment at CERN offers the unique opportunity of studying the three fields of hadron physics within one experiment using flexible beams and spectrometers setups. As most of the beam time has so far been devoted to experiments using muons (deep inelastic scattering - DIS and hard interactions) most of this report will be devoted to first results on this topic. At the end of last year a first pilot run with pions has been performed aiming at the measurement of polarizabilities and diffractive meson production. A first glimpse to this program will end this report.

THE COMPASS EXPERIMENT

The COMPASS experiment at the CERN SPS is a modern 2-stage magnetic spectrometer with a flexible setup to allow for a variety of physics programs to be performed with

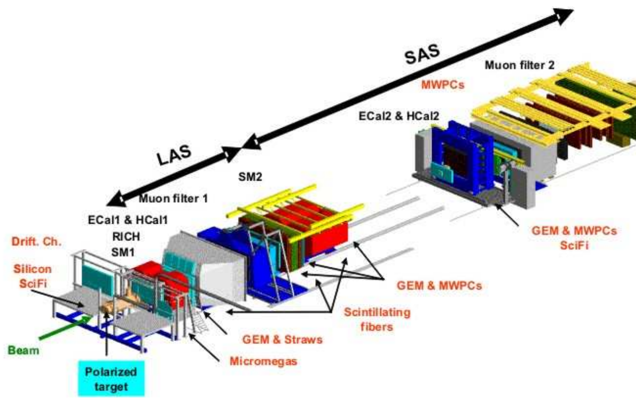

FIGURE 1. Layout of the COMPASS experiment at the CERN SPS

different beams (fig. 1). Common to all measurements is the requirement for high beam intensity and interaction rates with the needs of a high readout speed. The spectrometer is equipped with tracking systems based on silicon detectors for high precision tracking in the target region, micromega and GEM detectors for small area and wire/drift chambers as well as straw tubes for large area tracking. Particle identification is performed in a large acceptance ring imaging cherenkov detector downstream of the first spectrometer magnet and in hadronic (HCAL) and electromagnetic (ECAL) calorimeters in both parts of the spectrometer. The calorimeters are also used for the energy reconstruction of neutral particles. Both parts of the spectrometer are also equipped with muon detectors.

For measurements with a polarized nucleons a polarized target is installed about 3m upstream of the first magnet. It consists of two independent target cells filled with ^6LiD crystals mounted inside a very homogeneous solenoidal field of 2T. Using the technique of dynamic nuclear polarization 50% of the nucleons could be polarized with a degree polarization of more than 50%. The two target cells are thereby operated with opposite polarization to reduce systematic effects on asymmetry measurements owing to time dependent performance of the apparatus. The study of exclusive reactions using hadron beams requires a short solid target inside a veto-detector surrounded by silicon telescopes. The veto-detector is sensitive to charge and neutral particles with small openings in forward and backward direction.

The trigger system is mostly based on scintillator hodoscopes mounted in front of the target and downstream of the second magnet. Using a muon beam deep inelastic scattering (DIS) at large Q^2 is selected as well as low Q^2 events (quasi-real photons) with accompanying hadrons observed in HCAL. For diffractive and Primakoff scattering with hadron beams the target is surrounded by a veto box and small multiplicity events are selected by means of a scintillator and within an online event filter operated inside the event building computers.

PHYSICS RESULTS WITH MUON BEAMS

Spin-structure functions

The low energy description of the nucleons spin is based on the SU(6) wave functions for non-interacting constituent quarks of spin $\frac{1}{2}$ where two quarks are spin-aligned and one quark spin-antialligned making a total spin of $\frac{1}{2}$ for the nucleon. In turn, at small distance scales the nucleon is described in terms of QCD where quarks interact among each other via gluons. The resulting sharing of the nucleons momentum is described via structure functions (number densities) which are a function of the Bjorken variable x denoting the momentum fraction of a constituent and the energy scale Q^2 (which sometimes is identified with a spatial resolution scale). Quarks and gluons are not independent partners and the repartitioning of kinematic variables when changing the energy scale is described by the DGLAP equations. Measurements of the quark helicity within a polarized nucleon has been performed by a number of experiments using DIS on polarized nucleons at various Q^2. The pictorial interpretation of the results are not straightforward but its safe to say that quarks only carry part of the nucleons spin. Owing to the axial anomaly (coupling of quarks and gluons) the singlet axial charge a_0 (which enters the cross section asymmetries) combines spin contributions of quarks $\Delta\Sigma$ and gluons ΔG

$$a_0 = \Delta\Sigma - \frac{3\alpha_a\left(Q^2\right)}{2\pi}\Delta G \tag{1}$$

$$with\ \Delta\Sigma = \Delta u + \Delta d + \Delta s = 2\left\langle S_z^{quark}\right\rangle \tag{2}$$

Using a QCD analysis of the data we can extract values for $\Delta\Sigma \sim 0.2$. The accuracy is limited by the data quality at very low values of x, as $\Delta\Sigma$ is obtained from the integral of the spin-dependent quark structure function $g_1(x)$. The same analysis also allows to extract an estimate of the gluon spin structure-function $\Delta G(x)$. As experiments probe a_0 at different values of Q^2 we can use the evolution equations to obtain an estimate of the gluon contribution of the spin. However, the Q^2 range is small and thus uncertainties on $\Delta G(x)$ are large.

Measurement of A_1 on the deuteron

The high rate capability of COMPASS allows a precision study of the quark asymmetry A_1^d on the deuteron [1]. Using data taken in '02 and '03 we have collected about $3 \cdot 10^7$ DIS-events. The measured asymmetry A_1^d is obtained combining data from periods with opposite spin polarizations within the two target cells (see fig. 2 left). Thus, acceptance effects cancel out. We can translate the asymmetries into the polarized quark distribution functions normalizing the measured asymmetry to the unpolarized cross section determined by the structure function $F_2(x)/2x$ and the ratio of longitudinal to transverse cross

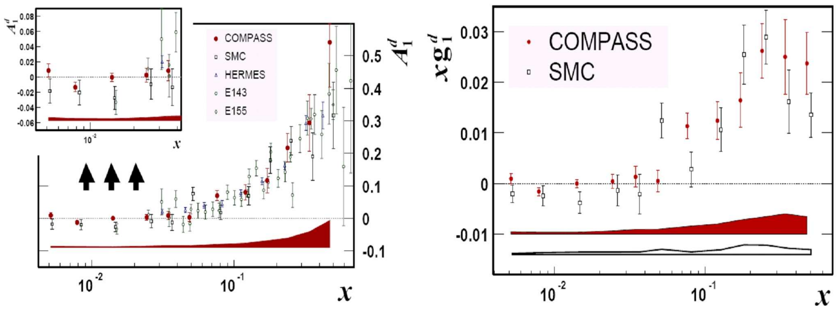

FIGURE 2. Left: Measured asymmetry using DIS events on the deuteron. The data are compared to results from previous experiments. The area shaded in dark red denotes the systematic uncertainties. The inlet depicts the results for small values of x, where COMPASS has the largest impact. Right: Results for $x \cdot g_1(x)$ extracted from the measured asymmetry. Data are taken at large Q^2 and compared to results from the SMC experiment. Bands for systematic uncertainties are given for both data sets (COMPASS: dark red)

section R.

$$g_1^d = \frac{F_2^d}{2x(1+R)} A_1^d \tag{3}$$

The results for $x \cdot g_1(x)$ extracted from the measured asymmetry are shown in the right of fig. 2. The data are taken at large Q^2 and are compared to results from the SMC experiment. Systematic uncertainties are marked by bands and are given for both data sets (COMPASS: dark red). The high precision of the new COMPASS data at low x help to better define the integral over $g_1(x)$ and thus allow to reduce the uncertainties on $\Delta\Sigma$ by a factor 2.

$$\Delta\Sigma = \ 0.237^{+0.024}_{-0.029} \tag{4}$$

The Gluon Spin Contribution

From the results obtained for the spin contribution of the quarks we conclude that the picture must be far more complicated than assumed at first. We can thus write the nucleons spin formally as a sum of four contribution.

$$\frac{1}{2} = S_z = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G \tag{5}$$

However, the interpretation and distinction between the different terms depends on the reference system and thus is not unique. While contributions to angular momenta are currently only accessible in principle[1] the COMPASS experiment aims at determining

[1] In the recent years a new mathematical formulation of angular momentum inside the nucleons in terms of so called generalized parton distributions has been found. However, this requires a large set of exclusive measurements over a wide kinematic range for which dedicated experiments and machines will have to

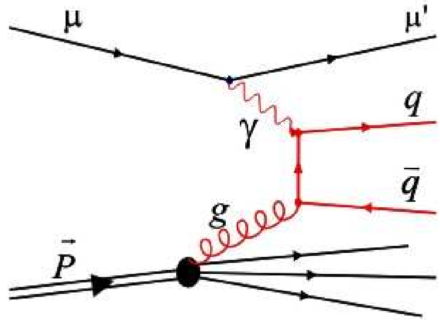

FIGURE 3. The γg-fusion process. It can be tagged using open charm or high p_T-hadron pairs in the final state.

the role of the gluon spin to this sum. This requires scattering processes which are a) sensitive to gluons and b) depict a sizeable analyzing power. In COMPASS the photon-gluon fusion process (PGF) is used, which can be tagged in two different ways.

1. The production of open charm is a very clean sign for the underlying hard QCD process as charm production in either fragmentation processes or via intrinsic charm is negligible. The energy scale of the process is determined by the minimal value $\sqrt{s} \geq 2m_c \simeq 3GeV/c^2$, thus we can use quasi real photons ($Q^2 \simeq 0$).
2. A second tag is the pair production of light hadrons at large transverse momentum ($p_T \geq 1GeV/c$) which also determines the scale of the underlaying process.

We will discuss the results for both processes studied.

ΔG via production of open charm

The PGF-process is depicted in fig. 3. The yield of charmed hadrons is about 1%, the analyzing power 10%. Using data obtained in 2002 and 2003 we have extracted a sample of D-mesons. This is done in two ways. D^0 candidates are selected via there decay $D^0 \rightarrow K\pi$ where the kaons are identified within the RICH. A very clean signal is obtained using reconstructed D^*-decays ($D^* \rightarrow D^0 \pi_{slow}$). These events are shown on the left of fig. 4. The full D^0 sample with and without D^*-tagging is summarized on the right of fig. 4 From these data we can extract ΔG using NLO calculations for the spin dependence of the $\gamma g-$process.The result is $\frac{\Delta G}{G} = -1.08 \pm 0.73$ at a mean value of $\langle x_G \rangle = 0.15$. We expect to improve the statistical error by about a factor two using 2004 data.

---

be constructed. It turns out that also the measurement of transversity inside the nucleon is connected to angular momentum via the determination of the Sivers function. However, this will be very model dependent.

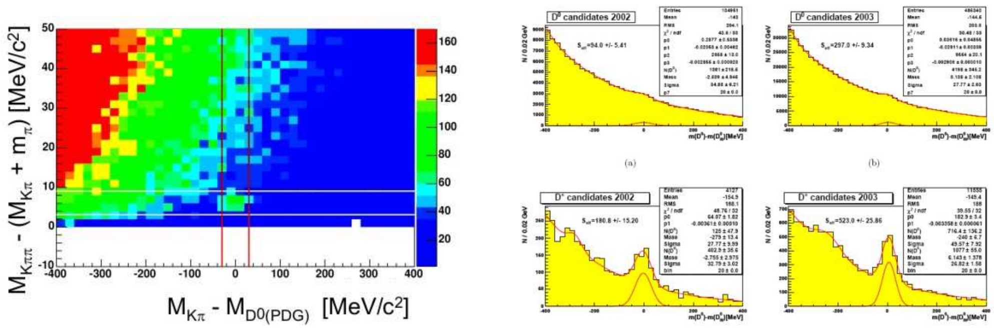

FIGURE 4. Left: $M(K\pi\pi) - M(K\pi)$ versus the $M(K\pi) - M(D^0)$ mass difference. Right: $(K\pi)$ invariant mass plots showing D^0-signals for two different selection schemes and the two data periods (left: 2002, right: 2003). Upper plots:$(K\pi)$ with hard K-identification. Lower plots:$(K\pi)$ combinations tagged by slow pions consistent with $D^* - D^0$ mass difference.

ΔG via production of high p_T hadron pairs

The channel of high p_T hadron pairs shares the virtue of high statistics with the drawback of systematic uncertainties on the role of background processes. The selection requires individual $p_T \geq 0.7$ combined with $p_{1T}^2 + p_{2T}^2 \geq (2.5(GeV/c)^2$ as well as $m(h_1, h_2) > 1.5 GeV/c^2$. The data set is divided into $Q^2 > 1(GeV/c)^2$ and $Q^2 \leq 1(GeV/c)^2$, which in our data set corresponds to quasi real photon production. For the high Q^2 sample the background processes are ordinary DIS events with fragmentation or gluon-Bremsstrahlung. However, as the quark asymmetries A_1^d are negligible at small x, these two processes do not dilute the asymmetry from the underlaying PGF process for the analyzing power and the partial cross section are taken from theory (and MC). The result using data from 2002 and 2003 is:

$$\Delta G/G = 0.06 \pm 0.31(stat.) \pm 0.06(syst.) \;\; for\ Q^2 > 1(GeV/c)^2; < x_B > \ 1.15 \quad (6)$$

For quasi-real photons the main background processes in the asymmetry are contributions from resolved photons (fluctuations of the photon into a hadron). As the polarized structure function of the photon is unknown, these processes contribute largely to the systematic errors as the contribution is model dependent and maximal and minimal scenarios are used to obtain a handle on their contribution. It should be noted that all corrections are only calculated in LO. From the measured asymmetry $A_{LL}/D = 0.002 \pm 0.019(stat)$ we derive a gluon polarization of

$$\Delta G/G = 0.024 \pm 0.089(stat) \pm 0.057(syst) \;\; for\ Q^2 \leq 1(GeV/c)^2; < x_B > \ 0.95 \quad (7)$$

Fig. 5 summarizes the COMPASS results for $\Delta G/G$ together with previous measurements from SMC and HERMES. It should be noted that previous determinations have not used the same method of subtracting background which is due to other processes. The small value of the gluon polarization at $x \sim 0.1$ can be compared to various models for the functional dependence $\Delta G(x)/G(x)$ assuming different values for the integral value. It seems that large values of $\Delta G/G$ are very unlikely.

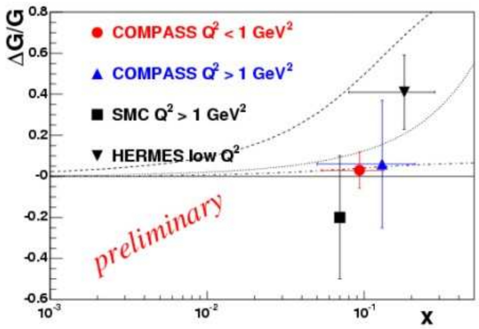

FIGURE 5. World data on direct measurements of the gluon polarization $\Delta G/G$ using high p_T hadron pairs [2]. The results from the COMPASS analysis for both ranges of Q^2 are shown together with previous analysis from SMC [3] and HERMES [4]. Note that the HERMES result does not include a systematic uncertainty linked to the background subtraction from other processes but PGF. Experimental curves taken from [5]

Transverse Spin Effects

In addition to the spin distribution functions G(x) and g_1(x) for longitudinally polarized nucleons the transversity function $\delta q(x)$ describes the distribution of transversely polarized quarks inside a transversely polarized nucleon. This function is more difficult to measure and to interpret, though formally it has to be considered on the same footing as the other structure functions. The reason for the experimentally difficult access to this function is that a physical measurement requires a suitable analyzing function. One possibility is a spin dependent fragmentation function (Collins function) in which a production asymmetry arises for hadron produced with larger transverse momentum (eq. 8). This asymmetry has to be measured w.r.t. to the spin direction of the nucleon and is called 'Collins function' [8]. We expect a modulation of the hadron intensity with $\sin(\phi+\phi_s)$. The plane of reference for all azimuth angles is the lepton scattering plane (see fig. 6 for the definition of angles).

$$A_T \propto \delta q(x) \cdot H_1(z, k_T) \tag{8}$$

HERMES has measured the combination of the two functions for the first time on polarized protons and obtained a non-zero result pointing to both functions being non zero [7]. The results for COMPASS measured on transversely polarized deuterons [6] are depicted in fig. 6. A second effect leading to non-zero asymmetries in reactions on transversely polarized targets is the Sivers effect [9] which correlates transverse momentum of quarks inside the nucleon with the transverse spin direction of the nucleon $\sin(\phi-\phi_s)$. Sivers and transversity/Collins effects can thus be disentangled by their different azimuthal dependence.

The COMPASS results show no sign of any asymmetry which might be explained by a cancelation of the effect by neutron and proton inside the deuteron.

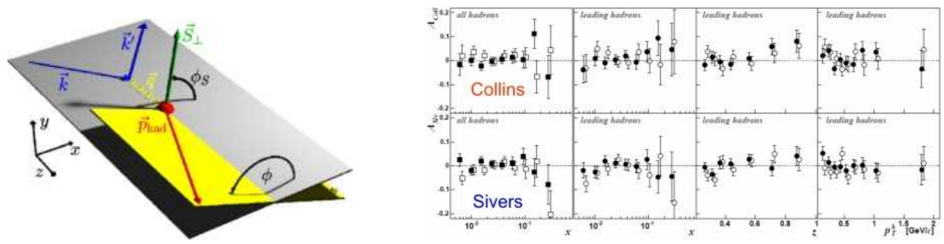

FIGURE 6. Left: Definition of angles in transversity measurements. Right: Azimuthal asymmetries obtained with a transversely polarized target in COMPASS. Upper: Collins angles, lower: Sivers angle.

DIFFRACTIVE PROCESSES AND HADRON STRUCTURE

Using an incoming hadron beam COMPASS aims at studying hadron polarizabilities using Primakoff reactions and light meson spectroscopy in diffractive and central production. In either case high rates and good acceptance should allow to improve over the existing data sets by about a factor 10 in the statistical sample.

A pilot run with Pions

In 2004 COMPASS has performed a short run with low intensity pions ($2 \cdot 10^6 \pi/spill$) impinging on a segmented lead (copper) target of 50% and 25% radiation length (two modes of running). The main purpose was as measurement of the pion polarizability using scattering off virtual photons on a lead nucleus. The Compton scattering process in inverse kinematics (fig. 7) is dominated by the Thompson cross section for point like particles and contains two terms describing the electric and magnetic polarizabilities of the hadron which can be separated by their different angular dependence (see eq. 9, where the cross section is given in the reference frame of the outgoing pion).

$$\frac{d\sigma_{\gamma\pi}(\theta,\omega)}{d\omega d\theta} = \frac{2\alpha^2}{m_\pi^2}\{F_{Th}^{\gamma\pi} + \frac{m_\pi \omega^2}{\alpha}\frac{\bar{\alpha_\pi}^2(1+\cos^2\theta)+\bar{\beta_\pi}^2\cos\theta}{(1+\frac{\omega}{m_\pi}\cos\theta)^3}\} \tag{9}$$

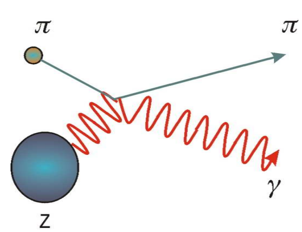

FIGURE 7. Sketch of the Primakoff reaction

$\bar{\alpha_\pi}$ and $\bar{\beta_\pi}$ are the electric and magnetic polarizabilities, respectively. Theoretically polarizabilities can be described in the framework of chiral perturbation theory, an effective field theory derived from QCD where mesons are the relevant degrees of freedom. The low energy expansion parameter is $\frac{m_\pi}{p}$ and higher order terms p^n contain

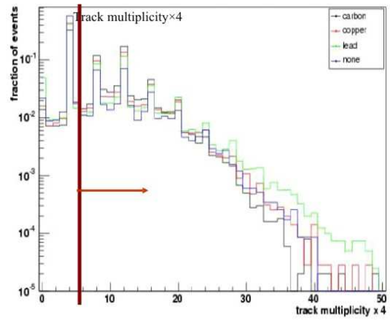

FIGURE 8. Track multiplicities (x4) as observed in the COMPASS silicon telescope downstream of the target using incoming pions. This info is used in a fast online data filter.

low energy constants derived from experiment. By now the calculations are of very high accuracy and constitute a challenge to experiments. While the first experiments using the same technique of Primakoff scattering obtained a value of $\bar{\alpha_\pi} = (6.8 \pm 1.4_{stat.} \pm 1.2_{sys}) \cdot 10^{-4} fm^3$ [10] a more recent extraction using threshold pion production in electron scattering off a proton obtained $\bar{\alpha_\pi} - \bar{\beta_\pi} = (11.6 \pm 0.5_{stat.} \pm 3.0_{sys} \pm 0.5_{model}) \cdot 10^{-4} fm^3$ [11]. These numbers can be compared directly if one assumes $\bar{\alpha_\pi} + \bar{\beta_\pi} = 0$

COMPASS has taken a first data set and within a few days of running about 35000 Primakoff events have been recorded with a 4-momentum transfer $t \leq 0.0015(GeV/c)^2$, which separates the Primakoff region from the diffractive background dominating a larger values of t. We expect to improve in statistical accuracy by about a factor 4-5 over the previous experiment from Serpukhov.

In addition, we have recorded events with neutral pions in the final state to obtain a new value for the chiral anomaly using the Primakoff reaction $\pi^- \rightarrow \pi^- \pi^0$. In the same data set we also have obtained events for diffractive production off a nucleus. Using a CH-target and a multiplicity trigger (fig. 8) we investigated reactions like $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ as well as $\pi^- p \rightarrow \gamma\gamma\pi^- p$. This programm is a continuation of the VES [12] and BNL [13] measurements on diffractive production on exotic mesons, however, with much higher beam energy.

Future of meson spectroscopy using central production

Central production ($pp \rightarrow p_{fast} p_{slow}\ X$) of a state X has proven to be a very useful tool in the search for exotic mesons and gluon rich states [14] (fig. 9) . As the cross section drops very fast with the mass of X we need high beam intensities and acceptance to extend the measurements into the region above 2 GeV/c^2. Using a 270 GeV/c proton beam, a liquid hydrogen target and full electromagnetic calorimetry we will investigate this reaction in 2007. Beam intensities of a few 10^7/spill are required to obtain a major gain in statistical significance as compared to previous experiments. This experimental challenge asks for fast triggering ($p_T - balance$, ECAL) and high resolution.

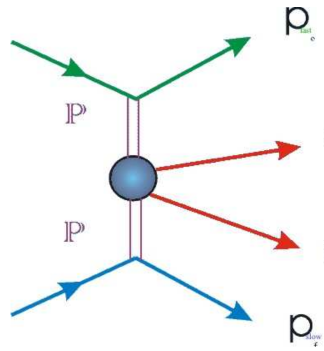

FIGURE 9. Sketch of central production of a state X decaying into $\eta\eta$.

SUMMARY

Using data taken in 2002-2003 COMPASS has made a major step forward in determining the gluon polarization in a direct measurement on polarized deuterons. The results obtained using high p_T hadron pairs points to a very small value for $\Delta G/G$ at $x_G \approx 0.1$ which does not favor expectations derived from QCD analysis of polarized DIS on nucleons. No significant sign for transversal asymmetries has been found so far, neither in transversity nor for the Sivers functions.

First data for the measurement of the pion polarizability has been collected and are currently being analyzed. This marks the beginning of the physics program with hadron beams within COMPASS, which is planned to be continued in 2007 with measurements on central production of hadrons.

REFERENCES

1. E.S. Ageev et al., Phys.Lett.B612:154-164,2005
2. E.S. Ageev et al., submitted to Phys.Lett.B
3. B. Adeva et al., Phys.Rev.D70:012002,2004
4. A. Airapetian et al., Phys.Rev.Lett.84:2584,2000
5. M. Gluck, E. Reya, M. Stratmann, W. Vogelsang, Phys.Rev.D63:094005,2001
6. V.Yu.Alexakhin et al. Phys.Rev.Lett.94:202002,2005
7. A. Airapetian et al., Phys.Rev.Lett.94:012002,2005
8. J. Collins, Nucl.Phys.396:161,1993
9. D. Sivers, Phys.Rev.D.41:83,1990
10. Yu.M. Antipov et al., Phys.Lett.B121:445,1983
11. J. Ahrens et al., Eur.Phys.J.A23:113-127,2005
12. D.V. Amelin et al. Phys.Lett.B356:595-600,1995
13. E.I. Ivanov et al. Phys.Rev.Lett.86:3977-3980,2001
14. D. Alde et al., Phys.Lett.B205:397,1988 and D. Barberis et al., Phys.Lett.B397:339-344,1997